Appendix I
Dry-Weather Model Configuration, Calibration, and Validation

I. Dry Weather Model Application

I.1 Introduction

The variable nature of bacteria sources during dry weather required an approach that relied on detailed analyses of flow and water quality monitoring data to identify and characterize sources. This TMDL used data collected from dry-weather samples to develop empirical equations that represent water quantity and water quality associated with dry-weather runoff from various land uses. For each monitoring station, a watershed was delineated and the land use was related to flow and bacteria concentrations. A statistical relationship was established between areas of each land use and flow and bacteria concentrations.

To represent the linkage between source contributions and in-stream response, a mass balance spreadsheet model was developed to simulate source loadings and transport of bacteria in the impaired streams and streams flowing to impaired beaches. The model estimates bacterial concentrations to develop load allocations and to allow for future incorporation of new data. This predictive model represents the streams as a series of plug-flow reactors, with each reactor having a constant source of flow and bacteria. A plug-flow reactor can be thought of as an elongated rectangular basin with a constant level in which advection (unidirectional transport) dominates (Figure I-1).

The model segments are assumed to be well mixed laterally and vertically at a steady-state condition (constant flow and constant input). Variations in the longitudinal dimension are what determine any changes in parameters of concern. A "plug" of a

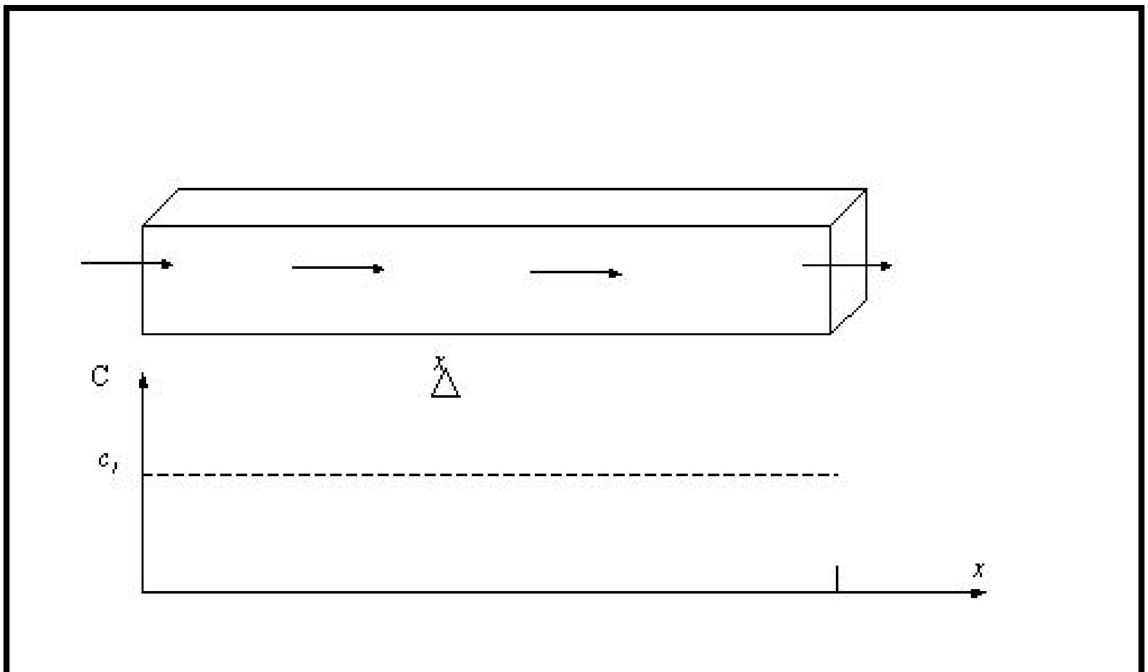

Figure I-1. Theoretical plug-flow reactor.

conservative substance introduced at one end of the reactor will remain intact as it passes through the reactor. The initial concentration of bacteria can be entered for the injection point. At points farther downstream, the concentration can be estimated based on first-order die-off and mass balance.

This modeling approach relies on basic segment characteristics, which include flow, width, and cross-sectional area. Model input for the flows and bacteria concentration of dry-weather urban runoff was estimated using regression equations based on analyses of observed dry-weather data. It is important to note that because each of these model parameters was estimated, the accuracy of the model is subject to the accuracy of the estimations. Bacteria concentrations in each reactor, or segment, are calculated using water quality data, a bacteria die-off rate, basic channel geometry, and flow. Bacteria die-off rates, which can be attributed to solar radiation, temperature, and other environmental conditions, were considered first-order.

I.2 Model Configuration

Conceptually, the streams are segmented into a series of plug-flow reactors defined along the entire length of the stream to simulate the steady-state distribution of bacteria along its length. Multiple source contributions in a reactor are lumped and represented as a single input based on empirically derived inflows and bacteria concentrations (see Sections I.2.2 and I.2.3. The model is one-dimensional (longitudinal) under a steady-state condition. Each reactor defines the mass balance for bacteria and water.

I.2.1 Physical Configuration

The first step in setting up and applying the model was the determination of an appropriate scale for analysis. Model subwatersheds were based on CALWTR 2.2 watersheds, stream networks, locations of flow and water quality monitoring stations, consistency of hydrologic factors, and land use uniformity. The subwatersheds used in the dry-weather model were the same as those used for the wet-weather model (see Appendix D).

Figure I-2 depicts an example of model connectivity of segments for the Chollas Creek watershed. Segments 1905, 1903, 1908, and 1907 are headwater segments. Segment 1902 begins where Segment 1903 and 1904 converge, and so forth. For each model segment, mass balance is performed on all inflows from upstream segments, input from local watershed runoff, first-order bacteria die-off, stream infiltration and evaporation, and outflow.

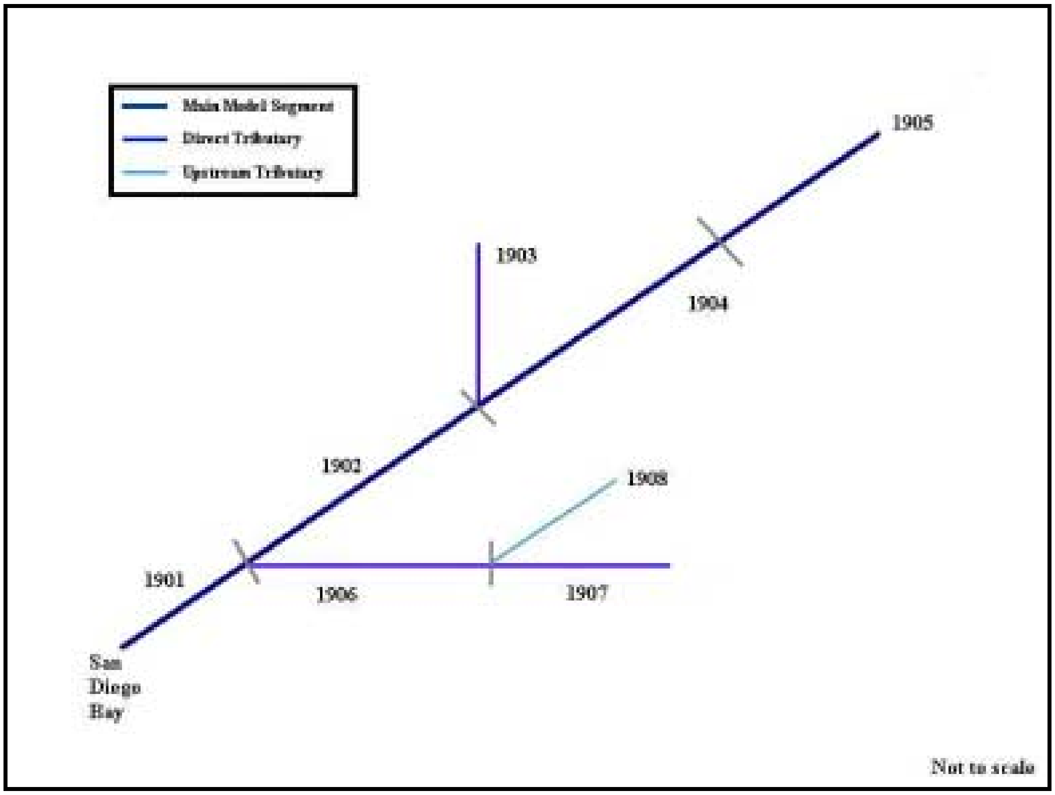

Figure I-2. Schematic of model segments for Chollas Creek and its tributaries.

Using an upstream boundary condition of initial concentration (C_0) for inflow, the final water column concentration (C) in a segment can be calculated using the decay equation given below:

$$\frac{dc}{dt} = -kc \qquad \text{or} \qquad C = C_0 e^{-kt} = C_0 e^{-\left(k\frac{x}{u}\right)}$$

where

C_0 = initial concentration (#/100 mL)
C = final concentration (#/100 mL)
k = die-off rate (1/d)
χ = segment length (mi)
u = stream velocity (mi/d)

At each confluence, a mass balance of the watershed load and, if applicable, the load from the upstream tributary is performed to determine the change in concentration. This is represented by the following equation:

$$C_0 = \frac{Q_r C_r + Q_t C_t}{Q_r + Q_t}$$

where

Q = flow (ft^3/s)
C = concentration (#/100 mL)

In the previous equation, Q_r and C_r refer to the flow and concentration from the receiving watershed and Q_t and C_t refer to the flow and concentration from the upstream tributary. The concentration calculated from this equation is then used as the initial concentration (C_0) in the decay equation for the receiving segment.

Precise channel geometry data were not available for the modeled stream segments, and therefore stream dimensions were estimated from analysis of observed data. Analysis was performed on streamflow data and associated stream dimension data from 53 USGS gages throughout southern California. For this analysis, it was assumed that all streamflow at these gages less than 15 ft^3/s represented dry-weather flow conditions. Using this dry weather data, the relationship between flow and cross-sectional area was estimated (R^2 = 0.51). The following is the resulting regression equation relating flow to cross-sectional area:

$$A = e^{0.2253 \times Q}$$

where

A = cross-sectional area (ft^2)
Q = flow (ft^3/s)

In addition, data from the USGS gages were used to determine the width of each segment based on a regression between cross-sectional area and width. The best relationship (R^2 = 0.75) was based on the natural logarithms of each parameter. The following is the resulting regression equation from the analysis:

$$LN(W) = (0.6296 \times LN(A)) + 1.3003 \quad \text{or} \quad W = e^{((0.6296 \times LN(A)) + 1.3003)}$$

where

W = width of model segment (ft)
A = cross-sectional area (ft^2)

I.3 Estimation of Dry-Weather Runoff

Flow data were not available for many of the subwatersheds. Estimates of inflows from the subwatersheds to the stream model were obtained through analysis of available data. Monitoring studies for which dry-weather flow data were collected were available for Aliso Creek (performed by the Orange County Pubic Facilities and Resources Department and the Orange County Public Health Laboratory) and for Rose Creek and Tecolote Creek (performed by the City of San Diego). Information from these studies was assumed sufficient for use in characterizing dry-weather flow conditions for the entire study area. For each study, flow data were collected throughout the year at stations throughout the watersheds. This information was used to understand the relationship between land use and stream flow.

An analysis was performed using dry weather data from the Aliso Creek (27 stations), Rose Creek (3 stations), and Tecolote Creek (2 stations) subwatersheds to determine whether there is a correlation between the respective land use types and the average of dry-weather flow measurements collected at the mouth of each subwatershed. The resulting equation showed a good correlation between the flow and the commercial/institutional, open space, and industrial/transportation land uses ($R^2 = 0.78$). The following is the resulting equation from the analysis:

$$Q = (A_{1400} \times 0.00168) + (A_{4000} \times 0.000256) - (A_{1500} \times 0.00141)$$

where

Q = flow (ft^3/s)
A_{1400} = area of commercial/institutional (acres)
A_{4000} = area of open space, including military operations (acres)
A_{1500} = area of industrial/transportation (acres)

Figure I-3 shows the predicted and observed flow data used in this regression.

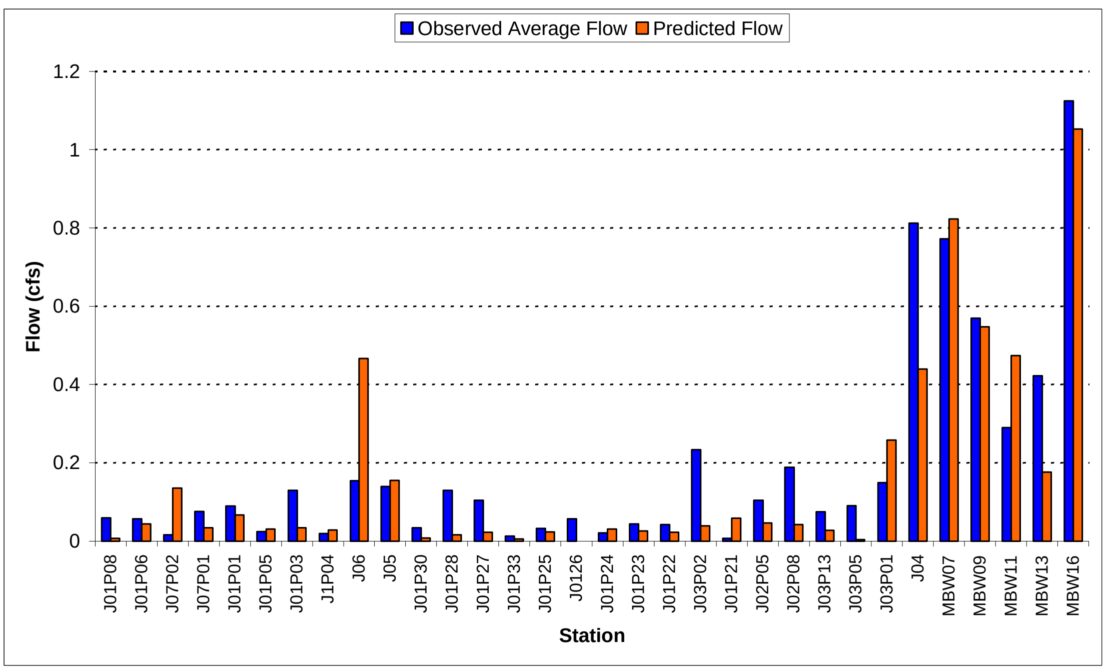

Figure I-3. Predicted and observed flows in Aliso Creek, Rose Creek, and Tecolote Creek.

I.5 Estimation of Bacteria Densities

Like flow data, bacteria data were not available for many watersheds modeled. However, bacteria data had been collected for Aliso Creek (Orange County Pubic Facilities and Resources Department), San Juan Creek (Orange County Pubic Facilities and Resources Department), and Rose Creek and Tecolote Creek in the Mission Bay area (City of San Diego). For each study, multiple bacteria samples were collected throughout the year at stations throughout the watersheds. For this study, the information was used to understand the relationship between land use and water quality.

An analysis was performed using data from Aliso Creek (27 stations), Tecolote Creek (5 stations), Rose Creek (4 stations), and San Juan Creek (9 samples) to determine the correlation between dry-weather FC concentrations, land use distribution, and the overall size of the subwatersheds. For comparison, geometric means were calculated for each station using all dry-weather data collected. Large data sets are required to reduce random error and normalize observations at each site. (For example, if a station has 40 dry-weather samples, the average geometric mean of bacteria concentrations can be used for that station with confidence that they are representative of the range of conditions that normally occur. However, if a station has only two samples, there is less confidence. It is critical that the data are normalized as well as possible before regression analysis so that variability does not propagate error.)

A regression analysis was then performed to determine whether there is a correlation between the representative geometric mean of FC data at each station, the percent of each land use category in the subwatershed, and the total subwatershed area. Results showed a good correlation between the natural log of FC concentrations and low-density residential, high-density residential, industrial/transportation, open space, transitional, commercial/institutional, and recreation land uses, as well as subwatershed size (R^2=0.74). The following is the resulting regression equation from the analysis of FC concentrations. Figure I-4 shows observed geometric means and predicted concentrations to allow comparison.

$$LN(FC) = 8.48 \times (\%LU_{LDR}) + 9.81 \times (\%LU_{HDR}) + 8.30 \times (\%LU_{IND}) + 8.46 \times (\%LU_{OPS}) + 10.76 \times (\%LU_{TRN}) + 6.60 \times (\%LU_{COM}) + 17.92 \times (\%LU_{PRK}) + 12.85 \times (\%LU_{OPR}) - 0.000245 \times A$$

where: FC = fecal coliform concentration (#/100 mL)
$\%LU_{LDR}$ = percent of low density residential
$\%LU_{HDR}$ = percent of high density residential
$\%LU_{IND}$ = percent of industrial/transportation
$\%LU_{OPS}$ = percent of open space, including military operations
$\%LU_{TRN}$ = percent of transitional space
$\%LU_{COM}$ = percent of commercial/institutional
$\%LU_{PRK}$ = percent of park/recreation
$\%LU_{OPR}$ = percent of open recreation
A = total area of watershed (acres)

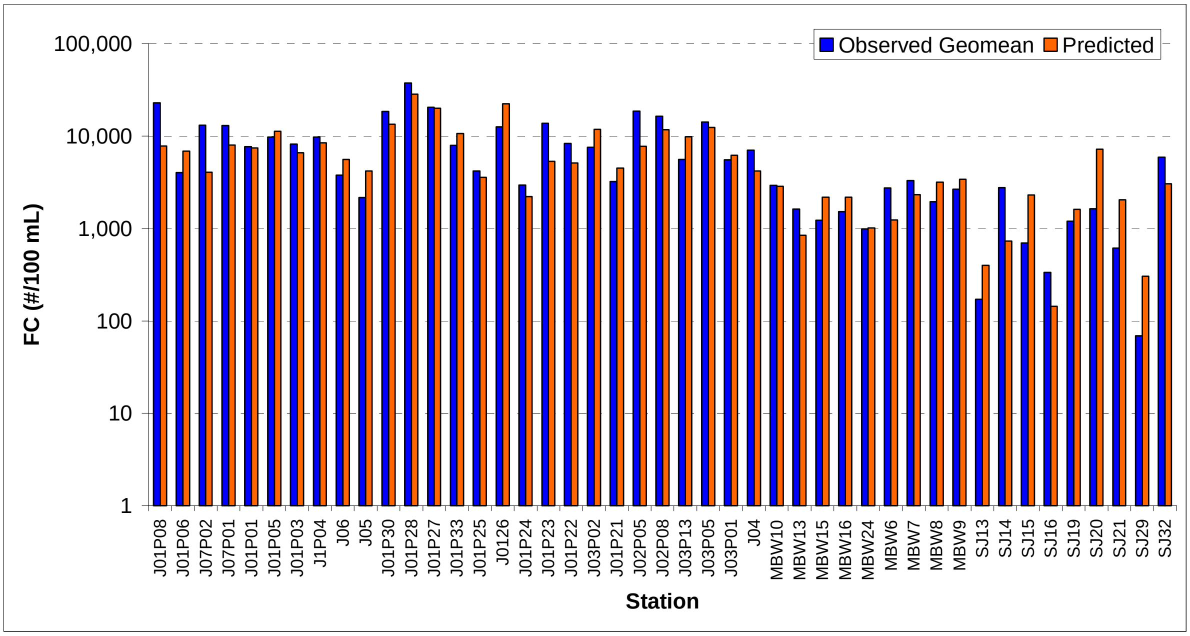

Figure I-4. Predicted versus observed fecal coliform concentrations.

The methodology for estimating FC concentrations was not as successful for prediction of TC and ENT. Similar regression analyses were performed to determine whether there are relationships between TC and ENT and land use and subwatershed size, but no acceptable correlations were found. As a result, a separate approach was used for estimating TC and ENT concentrations in dry-weather runoff for each subwatershed. Analyses of geometric means of FC data collected at each station were performed on similar geometric means of TC and ENT data collected at those same stations. The analyses resulted in a single, normalized value of FC, TC, and ENT at each station. Regression analyses were performed to determine whether there is a correlation between FC and levels of ENT and TC. Results showed a good correlation predicting TC and ENT as a function of FC (R^2=0.67 and R^2=0.77, respectively). The following are the resulting equations obtained (units of FC and TC/ENT are consistent):

$$TC = 5.0324 \times FC \quad \text{and} \quad ENT = 0.8466 \times FC$$

I.3 Model Calibration and Validation

The model was calibrated using data from Aliso Creek and Rose Creek. The calibration was completed by adjusting infiltration rates to reflect observed in-stream flow conditions and adjusting bacteria die-off rates to reflect observed in-stream bacteria concentrations. Following model calibration to in-stream flow and bacteria concentrations, a separate validation process was undertaken to verify the predictive capability of the model in other watersheds. Table I-1 lists the sampling locations used in

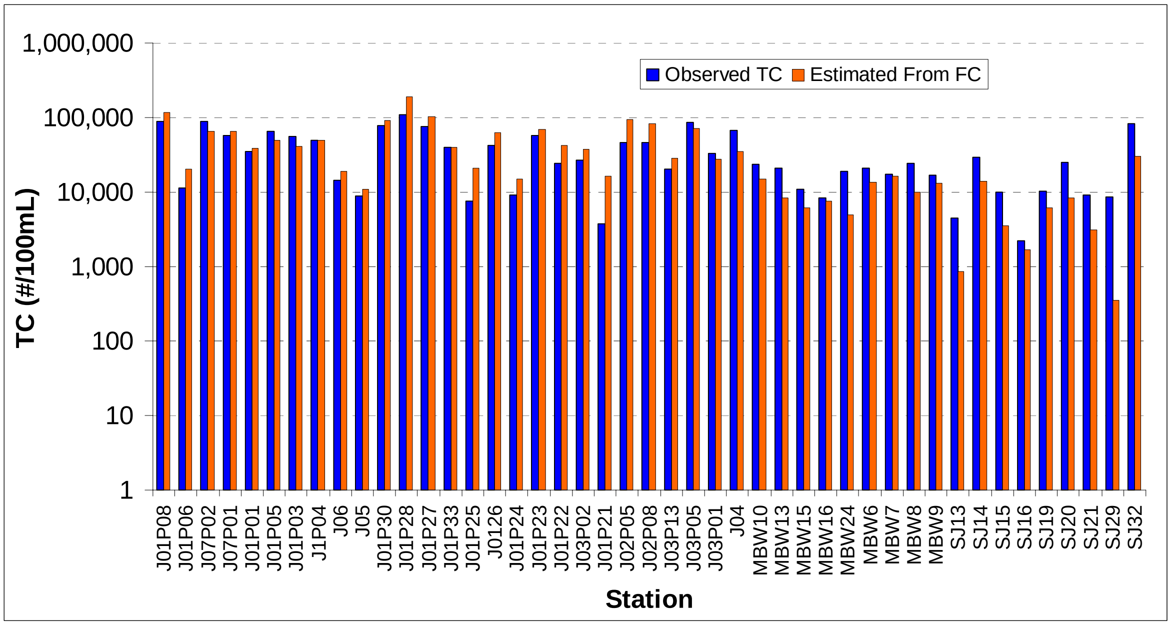

Figure I-5. Predicted versus observed total coliform concentrations.

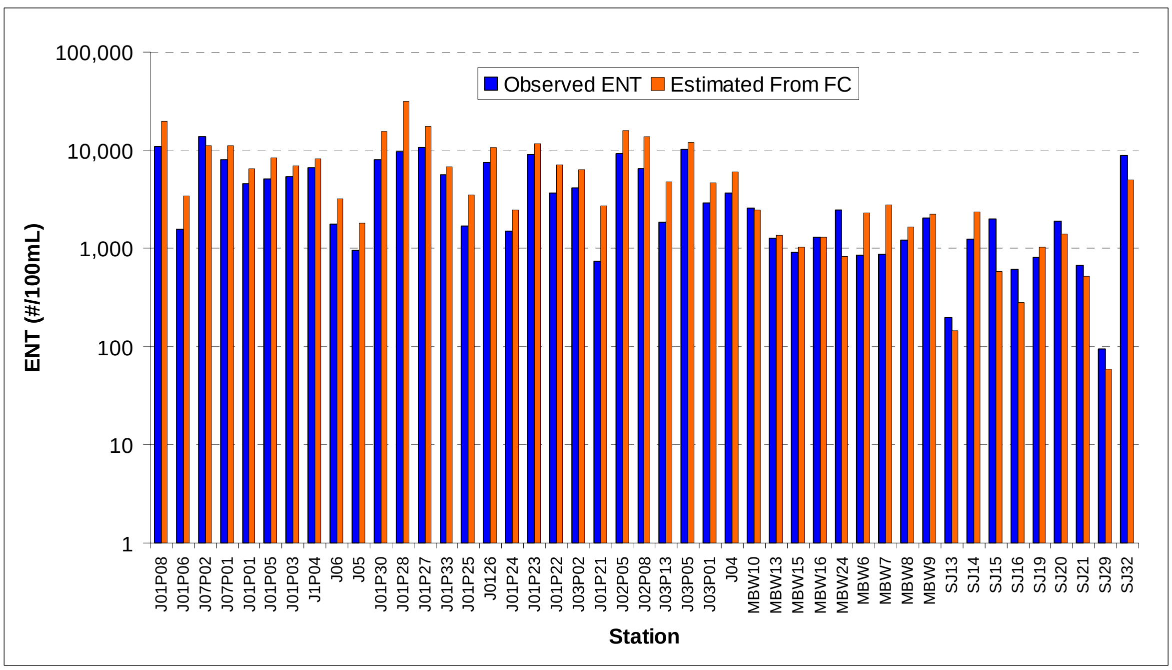

Figure I-6. Predicted versus observed enterococci concentrations.

calibration and validation, along with their corresponding watersheds. Figure I-7 shows the sampling locations in relation to the watersheds modeled for TMDL development.

Table I-1. Calibration and Validation Sampling Locations

Calibration – Flow and Bacteria		Validation – Flow		Validation – Bacteria	
Watershed	**Sampling Location**	**Watershed**	**Sampling Location**	**Watershed**	**Sampling Location**
208	J01P22	403	USGS11047300	402	SJ04
209	J01P23	1701	MBW06	403	SJ05
210	J01P28	1702	MBW07	405	SJ18
211	J01P27	1703	MBW10	406	SJ24
212	J06	1704	MBW08	408	SJ1
213	J01P05	1705	MBW09	409	SJ29 & SJ17
214	J01P01			411	SJ06
215	J01TBN8			413	SJ08 & SJ07
219	J04			414	SJ30 & SJ09
220	J03P13			416	SJ15
221	J03P01			1701	MBW06
1601	MBW20			1702	MBW07
1602	MBW17			1703	MBW10
1603	MBW15			1704	MBW08
1605	MBW11			1705	MBW09
1606	MBW13				
1607	MBW24				

In the model, infiltration rates vary by soil type. Stream infiltration was calibrated by adjusting a single infiltration value, which was varied for each soil type by factors established from literature ranges (USEPA, 2000) of infiltration rates specific to each soil type. The goal of calibration was to minimize the difference between averages of observed streamflows and modeled flow at each station location (Figure I-7). Nine stations were used in calibrating the infiltration rate. The resulting infiltration rates were 1.368 in/hr (Soil Group A), 0.698 in/hr (Soil Group B), 0.209 in/hr (Soil Group C), and 0.084 in/hr (Soil Group D). The infiltration rates for Soil Groups B, C, and D are within the infiltration range given in literature (Wanielisata et al., 1997). Soil Group A is below the range given in Wanielisata et al. (1997), however only one watershed in this TMDL is dominated by Soil Group A. Figure I-8 shows the results of the model calibration.

The modeled first-order die-off rate reflects the net effect on bacteria of various environmental conditions, such as solar radiation, temperature, dissolved oxygen, nutrients, regrowth, deposition, resuspension, and toxins in the water. The die-off rates for FC, TC, and ENT were used as calibration parameters to minimize the difference between observed in-stream bacteria levels and model predictions. Calibration results for FC, TC, and ENT are presented in Figures I-9 through I-10. Die-off rates were determined for FC (0.137 1/d), TC (0.209 1/d), and ENT (0.145 1/d). These values are within the range of die-off rates used in various modeling studies as reported by USEPA (1985). Sixteen stations were used in calibrating die-off rates.

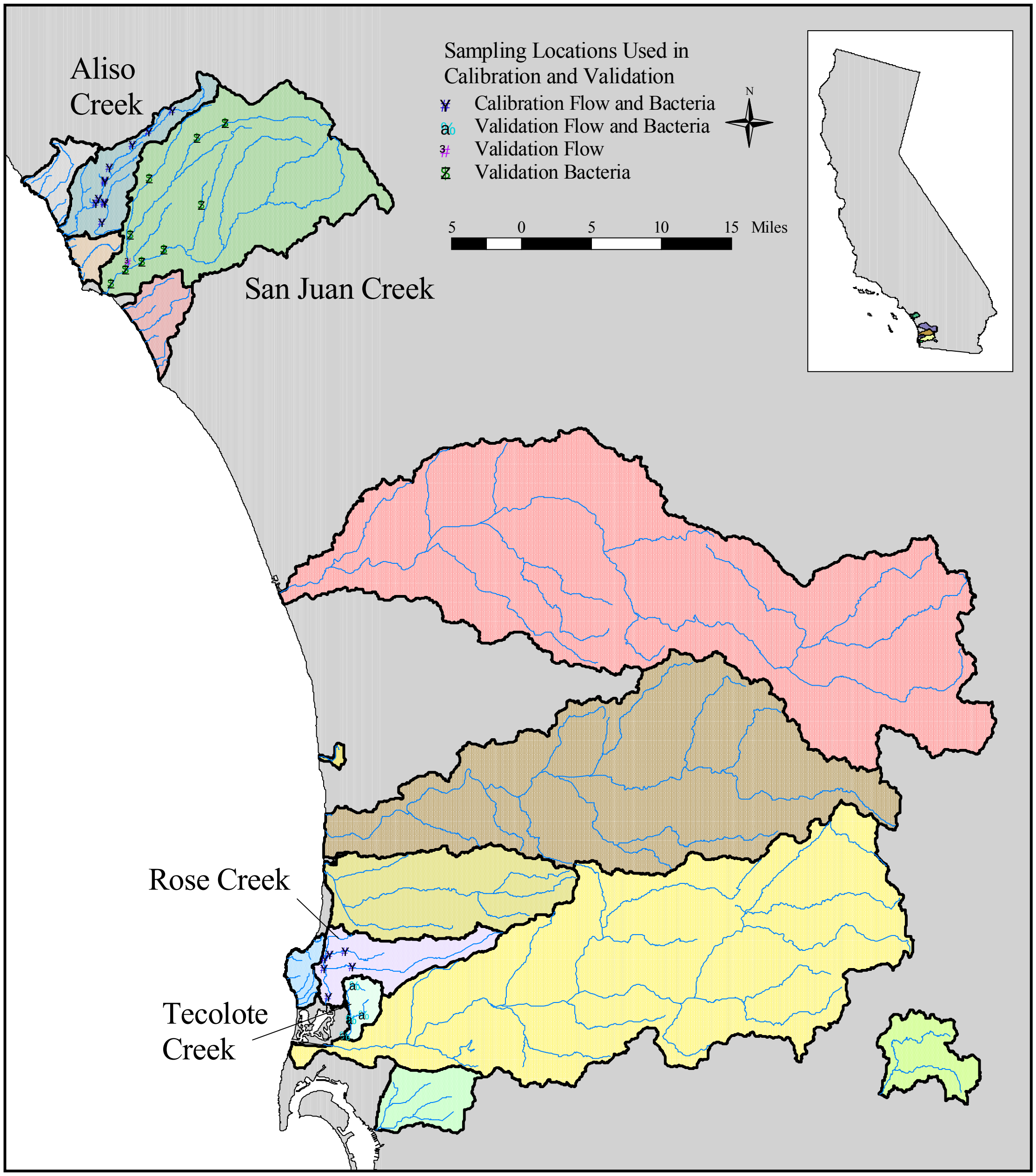

Figure I-7. Sampling locations used in model calibration and validation.

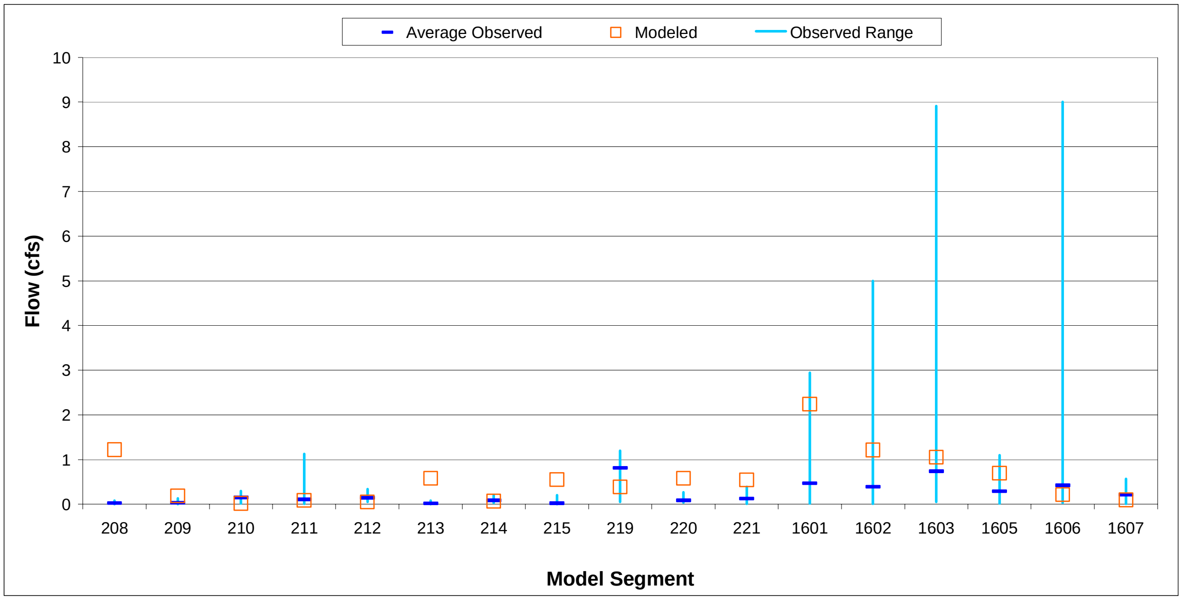

Figure I-8. Calibration modeled versus observed flows.

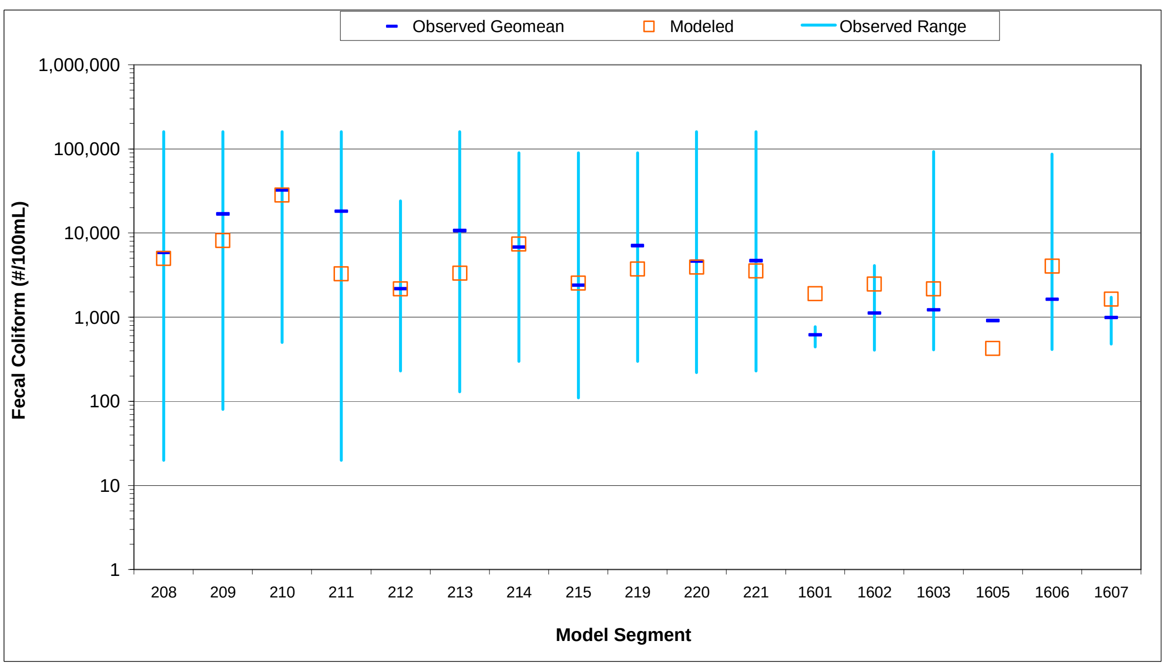

Figure I-9. Calibration modeled versus observed in-stream fecal coliform concentrations.

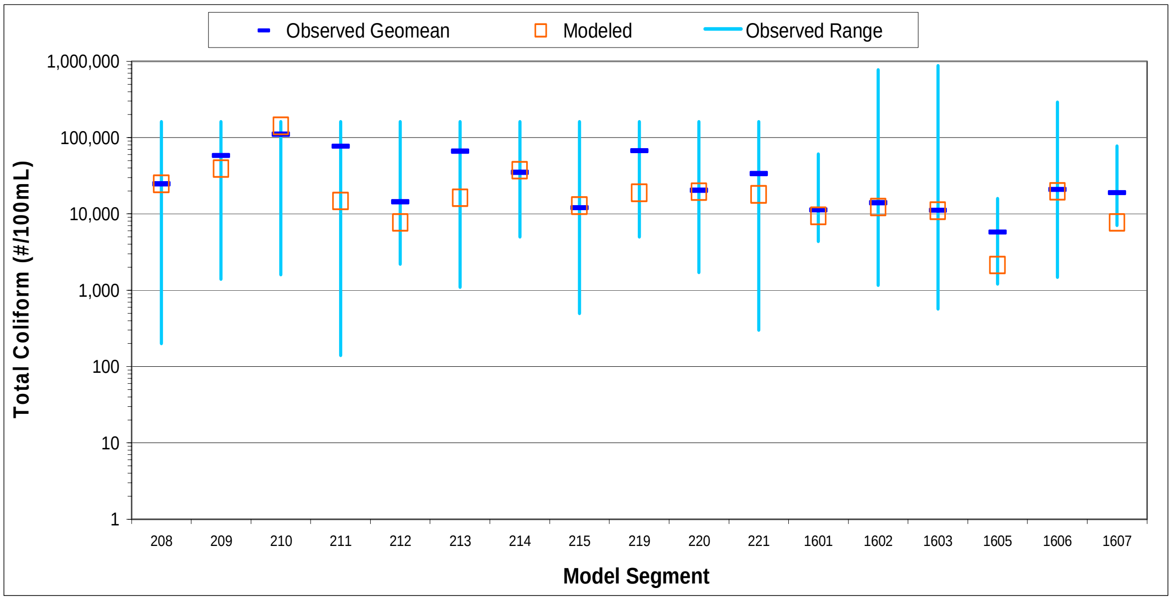

Figure I-10. Calibration modeled versus observed in-stream total coliform concentrations

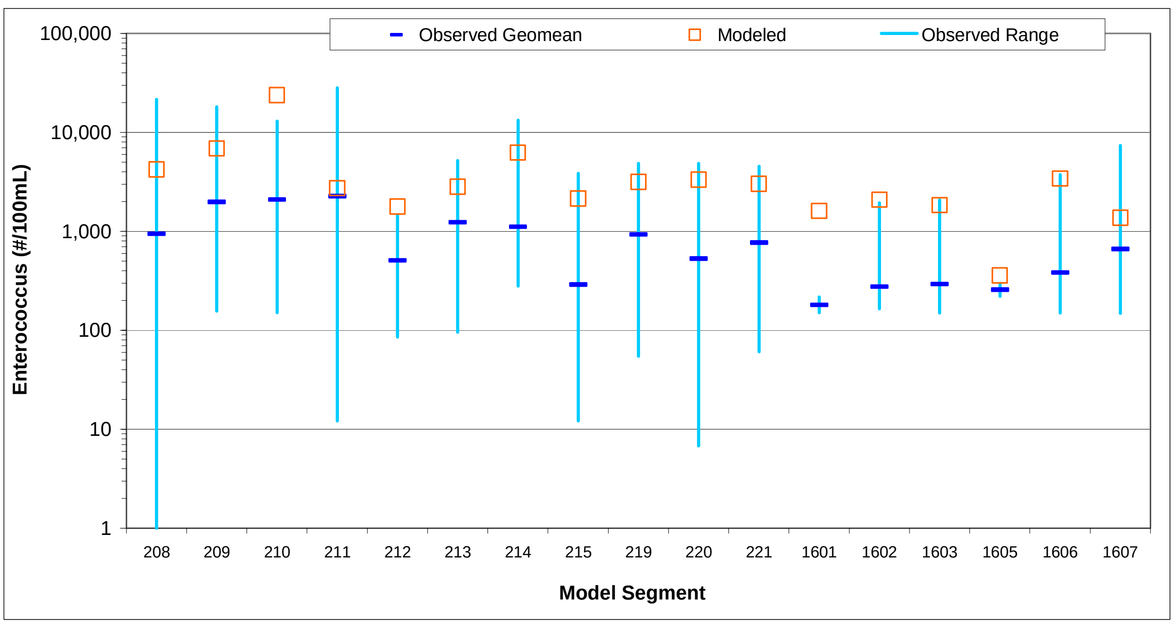

Figure I-11. Calibration modeled versus observed in-stream enterococci concentrations

The model was validated using six stations from San Juan Creek and Tecolote Creek. The model-predicted flows were within the observed ranges of dry-weather flows (Figure I-12).

Model validation to in-stream water quality was provided using 15 stations on Tecolote Creek and San Juan Creek. The results of the water quality validation are presented in Figures I-13 though I-15.

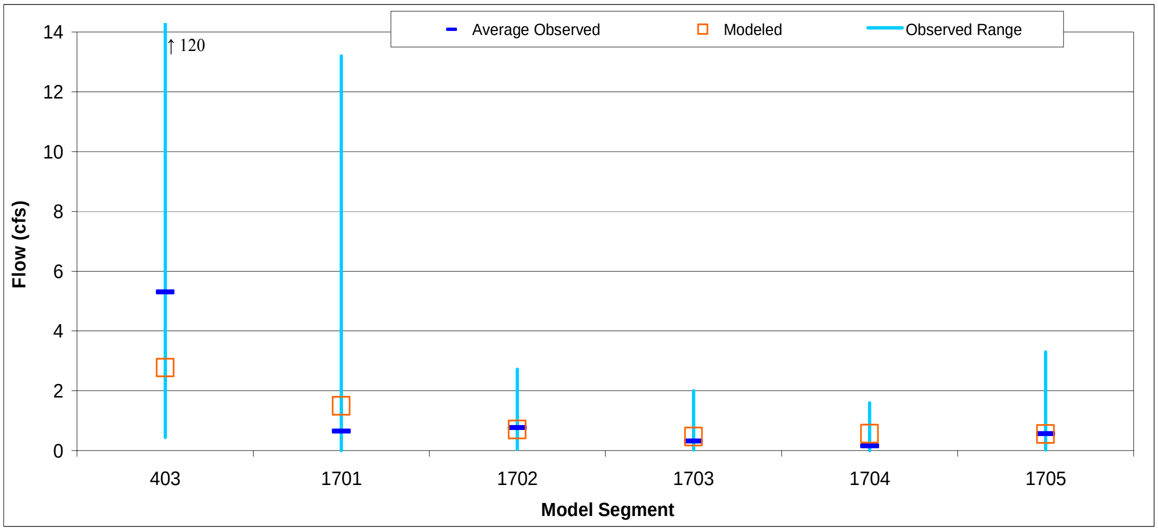

Figure I-12. Validation of modeled versus observed streamflow.

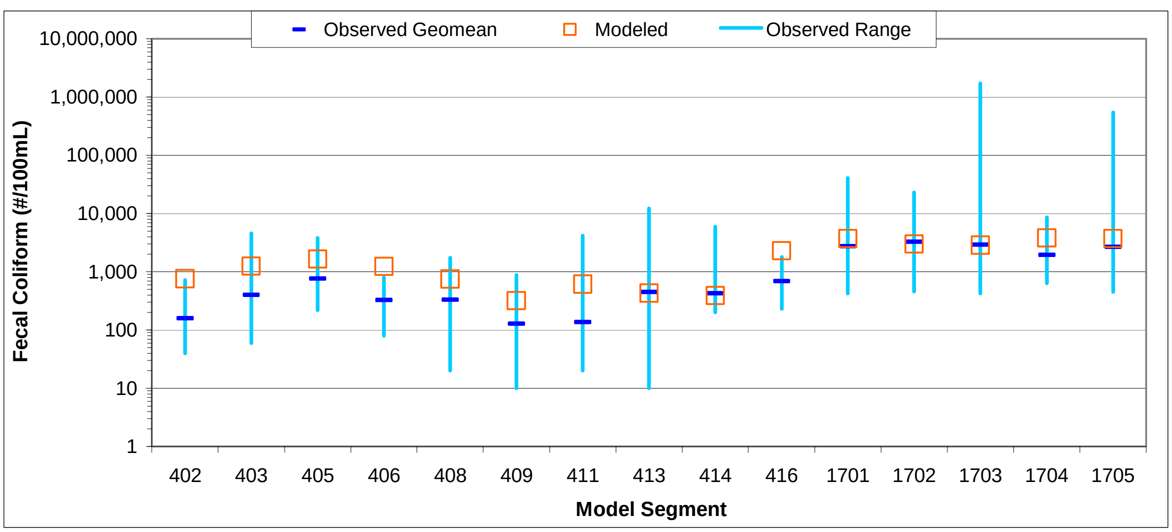

Figure I-13. Validation modeled versus observed fecal coliform concentration.

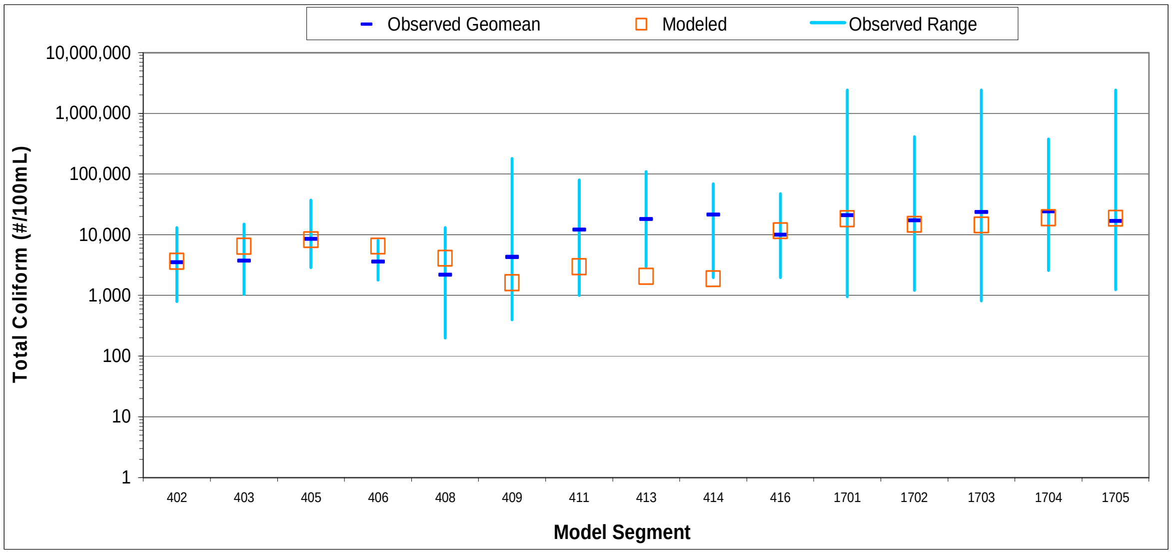

Figure I-14. Validation modeled versus observed total coliform concentration.

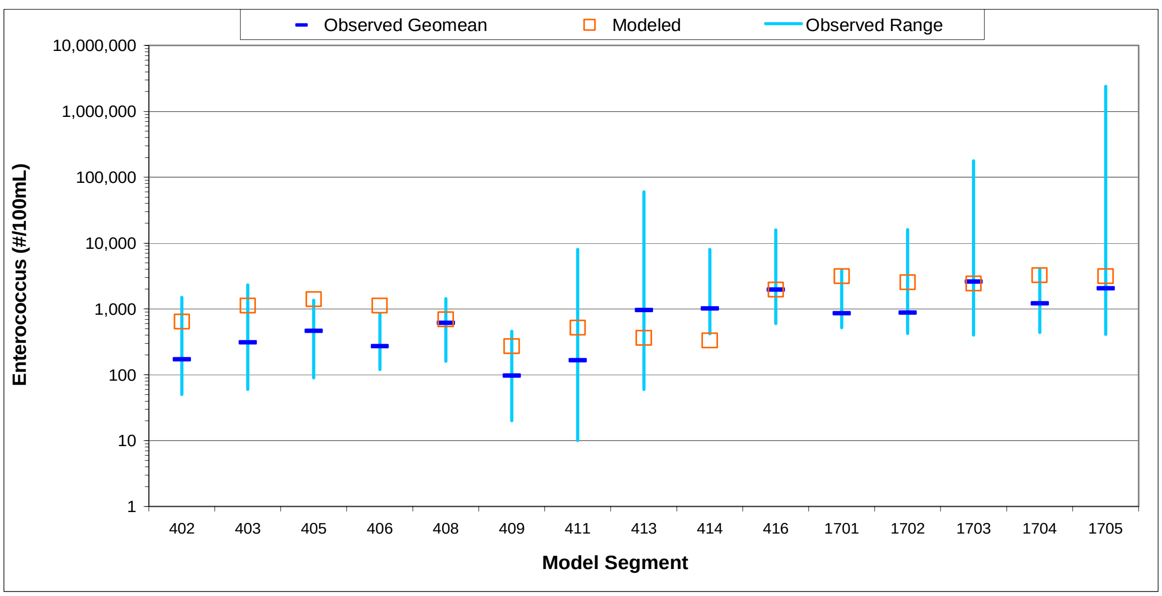

Figure I-15. Validation modeled versus observed enterococcus concentration.